

## **COVER LETTER**

**Title paper:** wave overtopping over sea dikes and impact forces on storm walls

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**Keywords:** storm walls, overtopping, impact forces, coastal infrastructures, non-breaking waves

# WAVE OVERTOPPING OVER SEA DIKES AND IMPACT FORCES ON STORM WALLS

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## ABSTRACT

Sea defense structures are necessary to protect the coastal areas and the hinterland from a severe storm surge. For the design of such structures, knowledge of their overtopping reducing effect and the resulting wave forces are indispensable. Therefore, model tests were carried out on dikes with storm walls at different locations in order to determine formulae for the prediction of the average overtopping discharge over the walls and wave impact forces on the walls. This paper gives a good overview of the obtained formulae.

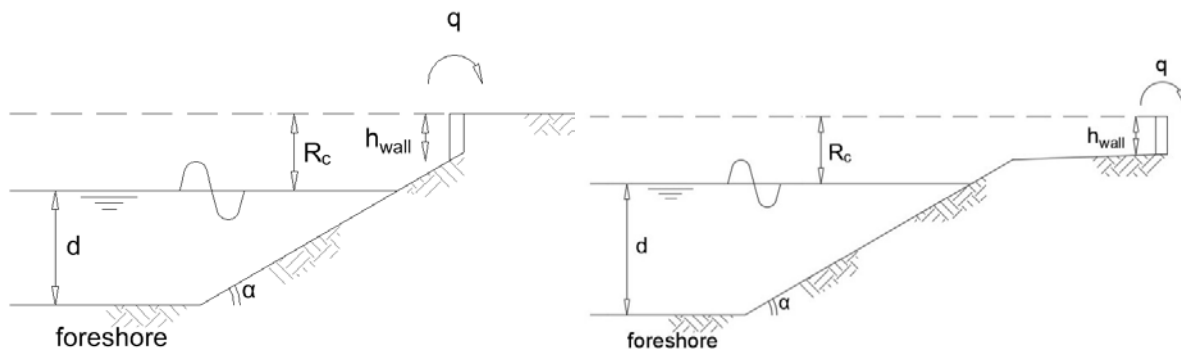
## INTRODUCTION

In recent years much attention was paid to the management and improvement of the dikes along coastlines. A lot of knowledge is gathered in the EurOtop (2007) manual, which will have an update in 2016. Part of the update for EurOtop II is based on an experimental research campaign at Ghent University which focuses on the reduction of wave overtopping over sea dikes with a smooth slope for non-breaking waves. Several crest modifications are introduced and their influence on the wave overtopping are expressed by means of reduction factors ( $\gamma$ ) to be included in (1).

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0.09 \cdot \exp \left[ - \left( 1.5 \cdot \frac{R_c}{H_{m0} \cdot \gamma} \right)^{1.3} \right] \quad (1)$$

where  $q$  represents the time averaged overtopping discharges [ $\text{m}^3/\text{m}/\text{s}$ ],  $g$  = gravity acceleration [ $9.81\text{m}/\text{s}^2$ ],  $H_{m0}$  = spectral wave height,  $R_c$  = freeboard and  $\gamma$  = reduction factor [-]. Equation (1) is the new standard equation to calculate overtopping discharges for non-breaking waves, introduced by van der Meer and Bruce (2014). In the current paper, only smooth dike slope (no roughness elements) and perpendicular waves are considered.

The crest modifications studied are a storm wall (with/without bullnose), a promenade and combinations of both, all located at crest level of the dike. To give the reader an idea on the kind of structures studied, a first view on them is shown in Figure 1: a dike slope with storm wall on the left, and a dike slope with promenade and storm wall at the right.



**Figure 1: Crest modifications to reduce wave overtopping. Dike with storm wall (left) and dike with promenade and storm wall (right)**

A second part of the research campaign by Ghent University investigates the wave impacts on the proposed measures who reduce wave overtopping. This part goes beyond the scope of the EurOtop II manual, but can be of main interest for governments, engineering companies and contractors who are

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actually designing and building the modified crests and coastlines. Apart from research conducted by Ghent University (almost) no literature information is available on wave impacts by post overtopping flows. Van Doorslaer et al. (2012) gives an overview on several test campaigns, and in Van Doorslaer et al. (2015a) the first results are published. There, an experimental formula is presented, which will also be used throughout this paper. It is an exponential relationship by the form

$$\frac{F_{1/250}}{\rho \cdot g \cdot R_c^2} = a \cdot \exp\left(-b \cdot \frac{R_c}{H_{m0}}\right) \quad (2)$$

By means of (2), wave height  $H_{m0}$  and freeboard  $R_c$  allow to calculate the impact force  $F$  [N/m] on the different geometries.  $\rho$  is the water density, and  $a$  and  $b$  are coefficients to be fitted for each geometry. Just like Goda (1985) suggested, the low exceedance value  $F_{1/250}$  is given which corresponds to the average impact value of the highest 1/250<sup>th</sup> of all waves in one test.

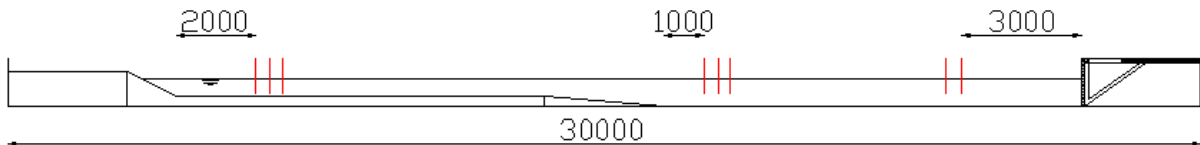
One can imagine that building a high(er) storm wall on a dike is a highly overtopping reducing measure, but will face high(er) wave impacts and thus will require high(er) amount of concrete and reinforcement. This paper does not make an economical comparison, but provides all required information for designers to make their own trade off matrix between the proposed measures in order to find the optimal modification where high reduction of overtopping and low cost price come together.

One important remark for this paper, is that all experiments were carried out with relatively deep water in front of the crest in comparison to the wave height. According to the EurOtop distinction between breaking and non-breaking waves, only non-breaking waves ( $\xi_{m-1,0} > 2.1$ ) are considered here. The situation with a mild sloping beach with shallow water in front of the sea dike is at this moment being studied by Flanders Hydraulics for wave overtopping (Altomare et al. 2016) and by Ghent University for impact forces (Streicher et al. 2016).

## TEST SET-UP

The dataset of over 1000 tests is achieved by means of experimental research carried out in the wave flume ( $L = 30.00\text{m}$ ,  $W = 1.00\text{m}$ ,  $H = 1.20\text{m}$ ) of the Coastal Engineering Department of Ghent University. In all tests, overtopping measurements are carried out. In 203 of those tests, wave impacts are measured by 2 load cells (see Figure 3), which lead to 406 data points on wave forces.

Waves are generated using a piston type wave paddle, and the steering of this paddle features active wave absorption. Each tested time series contains approximately 1000 waves, in order to obtain reliable average overtopping discharges and impact statistics. Waves are measured using resistance type wave gauges, positioned as shown in Figure 2: two in front of the wave paddle (on behalf of the active wave absorption), three at deeper water, and three in front of the structure (at a distance of about 0.4 times the wave length away from the structure). By means of these groups, incident and reflected wave conditions can be separated from each other and the incoming wave height can be determined, using the method by Mansard & Funke (1980). The height of the foreshore is 27cm, its length is 2 wavelengths. The water depth on the foreshore is large enough to avoid wave breaking. The wave spectra at the deeper water and on the foreshore were very comparable, no loss of energy takes place.



**Figure 2: Position of wave gauges in the 2D flume of Ghent University (distances in mm)**

The dike slope is 1(V):2(H) or 1(V):3(H), the dimensionless freeboard  $R_c/H_{m0}$  between 0.6 and 2.7 and the wave breaker parameter  $\xi_{m-1,0}$  is above 2.1. The wall is in all tests above water, being  $h_{\text{wall}} < R_c$ . The other important parameters will be given at each different geometry, along with a figure.

### Measuring wave overtopping

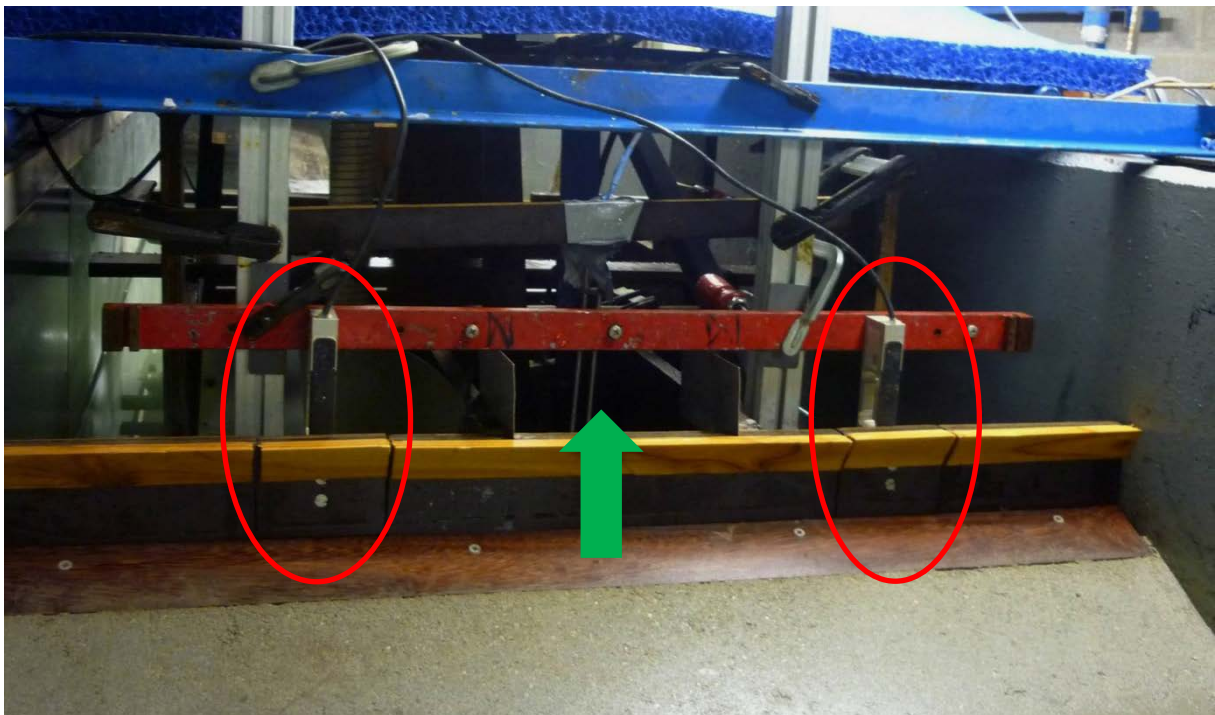
Wave overtopping is captured by a tray on top of the smooth dike slope, and lead to a 30 liter basin that is constantly weighed on a balance. When the basin is full, water is pumped back to the wave flume in order to maintain the correct water level in the flume during the test. Total overtopping volume can be deducted from the balance's weight registration in time.

Non-breaking wave conditions ( $\xi_{m-1,0} > 2.1$  in our dataset) are tested on a smooth dike slope ( $\gamma_f = 1$ ) with perpendicular wave attack ( $\gamma_\beta = 1$ ). Both a dike slope 1(V):2(H) and 1(V):3(H) are tested.

The majority of the tests are performed with a JONSWAP 3.3 spectrum while some are performed with a Pierson-Moskowitz spectrum, both single peak spectra. No influence of the spectrum on the overtopping volumes can be noticed for the range of dimensionless freeboards and tested spectra in the current data set.

### Measuring impact forces

Wave impacts are measured by means of 2 separate static load cells, left and right of the overtopping tray, attached to a 10cm wide part of the storm wall and mounted on a stiff frame (see Figure 3). The horizontal forces on a storm wall and storm wall with bullnose are recorded with 5kg load cells. To measure the uplift (vertical) forces on a storm wall with bullnose, 3kg load cells are used.



**Figure 3: Example case of a dike with storm wall and bullnose. 2 loose parts of the storm wall are attached to 2 force transducers (red circles) measuring the horizontal impacts, while the overtopping over the storm wall with bullnose is captured in the overtopping tray (green arrow).**

Forces are recorded using a sample frequency of 1000Hz and analyzed by means of in house developed peak detection software. Only the peaks of each impact are considered. In the analysis, a band-stop filter at 50Hz is used to avoid noise by the electricity net, a high pass filter of 0.01Hz and a low pass filter of 50Hz is used. A hammer test showed that the eigenfrequency of the storm wall is around 100Hz. At some tests, a small increase of the energy is noticeable around the 100Hz eigenfrequency showing resonance and leading to unrealistic high values. This is avoided by using a low pass filter of 50Hz, which still respects the energy in the actual impact. In the analysis a threshold value of 0.1N is used; lower values include too much noise and unreal "impacts" to the analysis.

For the tests regarding impacts, only Jonswap 3.3 wave spectra are used.

## RESULTS

In this section, the different geometries are discussed, with a view on the reduction of wave overtopping where a influence factor  $\gamma$  is given to include in (1), and with a view on the impact forces where coefficients  $a$  and  $b$  of (2) are given.

Before all influence factors are included in the formula, a dataplot of all tests is given in Figure 4:

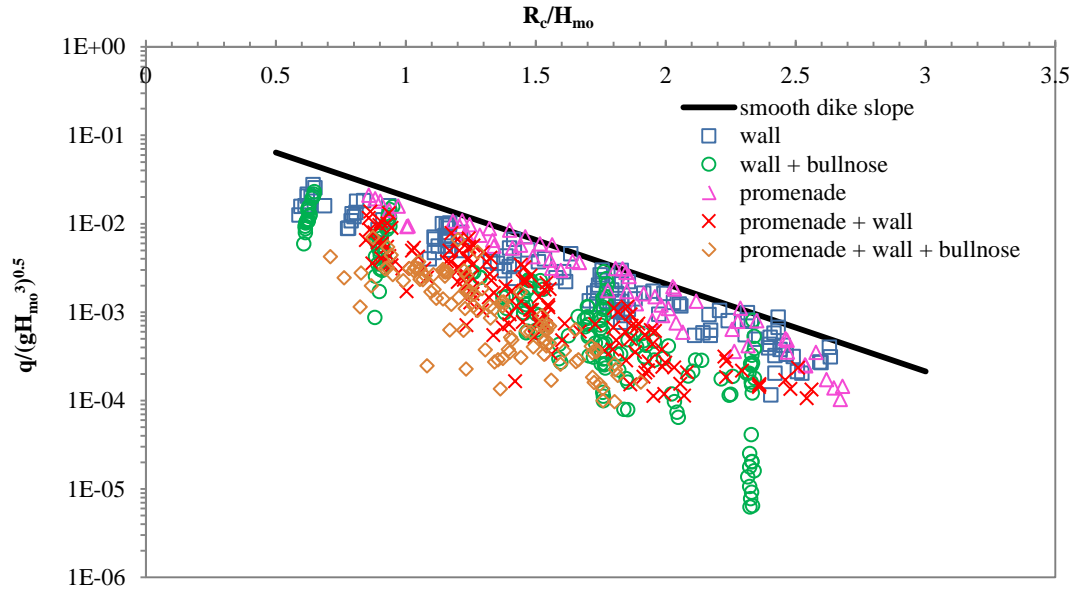


Figure 4: Overtopping over the different geometries without influence factors present in the graph

Figure 4 shows that all structures reduce wave overtopping quite good: the data points from the different geometries are all located below the reference line (1) for a smooth dike slope with all influence factors  $\gamma = 1$ .

When all influence factors are introduced on the horizontal axis ( $R_c/H_{m0}/\gamma$ ) with  $\gamma$  according to the formulae given in the next sections, Figure 4 changes into Figure 5. Data points are now much better predicted by the black reference line. This proves the quality of the  $\gamma$ -formulae as given in the next sections.

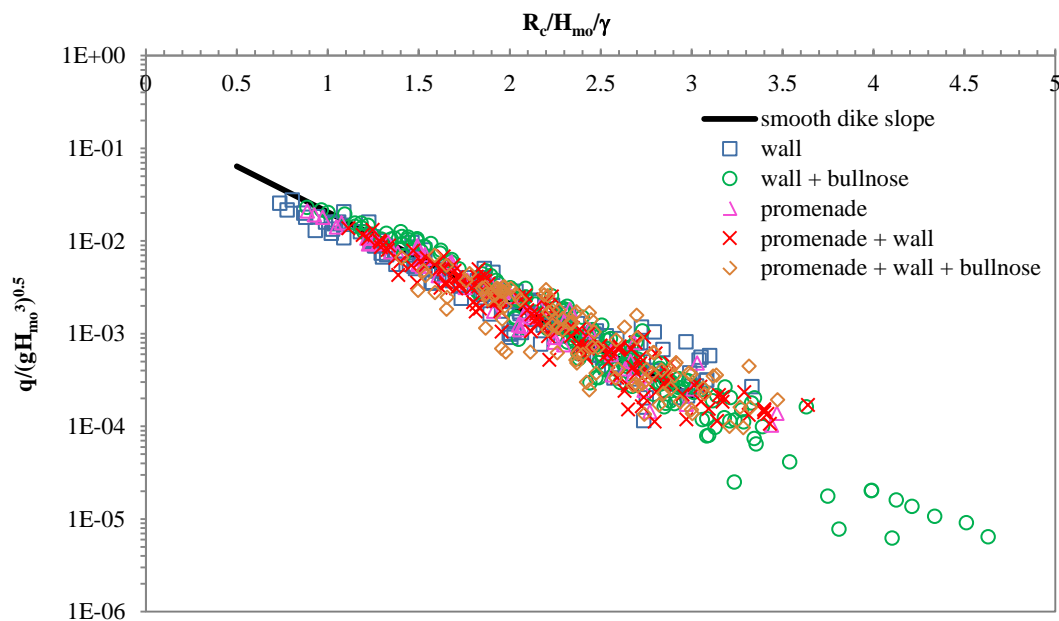


Figure 5: Overtopping over the different geometries with influence factors included in the graph

### Smooth dike slope with storm wall

The most straightforward method to reduce wave overtopping is by placing a storm wall at the edge of the slope, see Figure 6. 175 tests are carried out to measure wave overtopping, while in 27 of those (54 data points) also forces are measured. The range of parameters which is used for this geometry is given in Table 1.

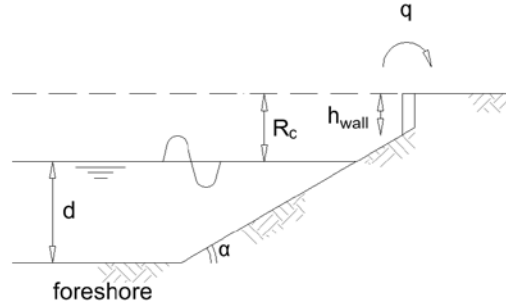


Figure 6: Storm wall on top of a dike slope

		Tests overtopping	Tests impacts
Slope angle of the smooth dike slope	$\cot(\alpha)$	2 and 3	2 and 3
Dimensionless freeboard	$R_c/H_{m0}$	0.60 – 2.60	1.10 – 2.60
Dimensionless wall height	$h_{wall}/R_c$	0.08 – 1.00	0.27 – 0.50
Wave steepness	$s_{m-1,0}$	0.007 – 0.052	0.007 – 0.040
Wave breaker parameter	$\xi_{m-1,0}$	2.20 – 4.80	2.27 – 4.80

Table 1: Summary of the test program on a smooth dike slope with storm wall

In the tests to reduce wave overtopping (without force measurements), the wall height is varied. In the impact tests, only a fixed wall height is used. The variation in  $h_{wall}/R_c$  then comes due to a variation in water level.

In Van Doorslaer et al. (2015b), the analysis on the reduction of wave overtopping is given in full depth, here the formulae and most important conclusions are repeated. The influence factor to be included in the exponential part of (1) is  $\gamma_v$  given in (3):

$$\gamma_v = \exp\left(-0.56 \frac{h_{wall}}{R_c}\right) \quad (3)$$

The analysis of the forces shows that the wave period and dike slope angle  $\alpha$  in our dataset ( $\cot(\alpha) = 2$  and 3)) have no influence. A low scattered relationship with  $a = 4.45$  and  $b = 1.49$  is found:

$$\frac{F_{1/250}}{\rho \cdot g \cdot R_c^2} = 4.45 \cdot \exp\left(-1.49 \cdot \frac{R_c}{H_{m0}}\right) \quad (4)$$

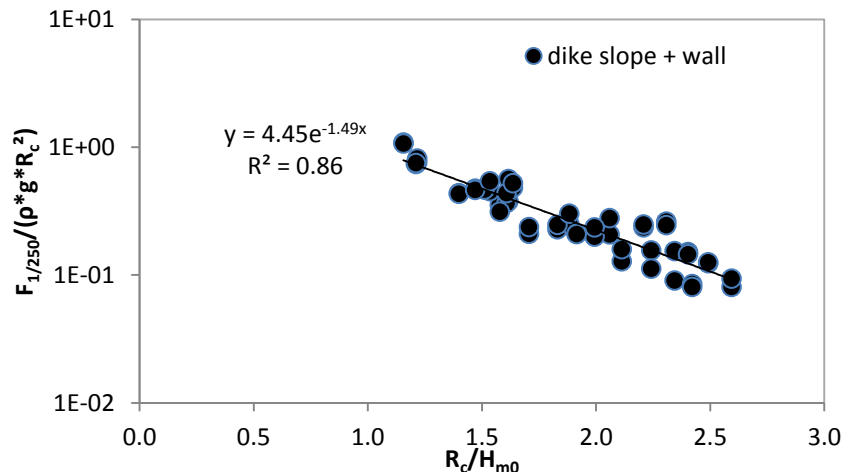


Figure 7: Impact forces on a storm wall

### Smooth dike slope with storm wall with bullnose

Next, a parapet nose, recurve wall or bullnose is added to the storm wall, see Figure 8. Further, the terminology “storm wall with bullnose” will be used. To study the overtopping reducing capacity (175 tests), different nose angles  $\varepsilon$  are tested going from  $15^\circ$  to  $60^\circ$ . Also the point where the bullnose starts, indicated by  $\lambda$ , being the height ratio of the bullnose height to the wall height, is varied. To study the impact forces (83 tests), only the optimal reductive measures are used:  $\varepsilon$  equal to  $30^\circ$  or  $45^\circ$ ,  $\lambda \geq 1/3$ . All parameters are given in Table 2.

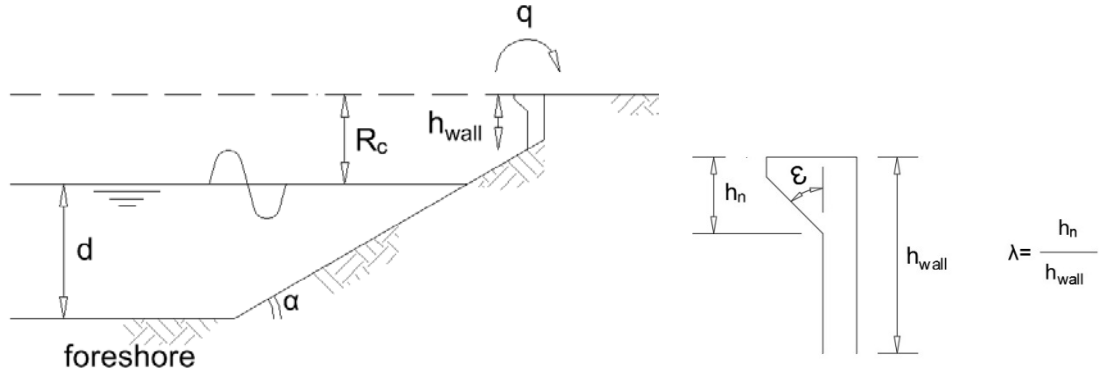


Figure 8: Storm wall with bullnose on top of a dike slope

		Tests overtopping	Tests impacts
Slope angle of the smooth dike slope	$\cot(\alpha)$	2 and 3	2 and 3
Dimensionless freeboard	$R_c/H_{m0}$	0.60 – 2.35	1.25 – 2.25
Dimensionless wall height	$h_{wall}/R_c$	0.10 – 0.90	0.27 – 0.50
Wave steepness	$s_{m-1,0}$	0.01 – 0.05	0.01 – 0.04
Wave breaker parameter	$\xi_{m-1,0}$	2.20 – 4.60	2.20 – 4.60
Bullnose angle	$\varepsilon$	$15^\circ, 30^\circ, 45^\circ, 60^\circ$	$30^\circ$ and $45^\circ$
Bullnose height ratio	$\lambda$	0.125 - 1	0.375

Table 2: Summary of the test program on a smooth dike slope with storm wall and bullnose

The influence factor to account for the effect of a bullnose is  $\gamma_{bn} \cdot \gamma_{s0,bn}$  to be multiplied by  $\gamma_v$  in (3). Combined, the formula to calculate overtopping becomes

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0.09 \cdot \exp \left[ - \left( 1.5 \cdot \frac{R_c}{H_{m0} \cdot \gamma_v \cdot \gamma_{bn} \cdot \gamma_{s0,bn}} \right)^{1.3} \right] \quad (5)$$

For  $h_{wall}/R_c \geq 0.25$ :

$$\gamma_{bn} = 1.8 \cdot \gamma_\varepsilon \cdot \gamma_\lambda \quad (6)$$

where:

$$\begin{aligned} \gamma_\varepsilon &= 1.53 \cdot 10^{-4} \varepsilon^2 - 1.63 \cdot 10^{-2} \varepsilon + 1 & \text{if } 15^\circ \leq \varepsilon \leq 50^\circ \\ \gamma_\varepsilon &= 0.56 & \text{if } \varepsilon > 50^\circ \\ \gamma_\lambda &= 0.75 - 0.20 \lambda & \text{if } 0.125 \leq \lambda \leq 0.6 \end{aligned}$$

For  $h_{wall}/R_c < 0.25$ :

$$\gamma_{bn} = 1.8 \cdot \gamma_\varepsilon \cdot \gamma_\lambda - 0.53 \quad (7)$$

where:

$$\begin{aligned} \gamma_\varepsilon &= 1 - 0.003 \varepsilon & \text{if } 15 \leq \varepsilon \leq 60 \\ \gamma_\lambda &= 1 - 0.14 \lambda & \text{if } 0.1 \leq \lambda \leq 1 \end{aligned}$$

The overtopping discharge over a smooth dike with storm wall and bullnose is dependent on the wave period or wave steepness. A wave with long wave period has the tendency to fill the space underneath the bullnose, so the rest of the incident wave observe the structure as a normal vertical storm wall. A wave with short wave period does not have this behavior. An influence factor,  $\gamma_{s0,bn}$ , is therefore introduced (only for this geometry) as:

$$\gamma_{s0,bn} = 1.33 - 10 \cdot s_{m-1,0} \quad (8)$$

An increased bullnose angle  $\epsilon$  reduces the amount of overtopping, but increases the impact forces on the construction. For this section, not only the horizontal impacts are considered, but tests have been redone to also measure the vertical impacts.

Similar to the previous geometry, the dike slope angle ( $\cot(\alpha) = 2$  or  $3$ ) and the wave period have no significant influence on the overtopping and are thereby not included as a parameter in the formula. The angle  $\epsilon$  of the bullnose and the kind of measurement (horizontal or vertical) both show a significant difference. Figure 9 shows the 4 different groups of data: a bullnose of  $30^\circ$  in full symbols, and a bullnose of  $45^\circ$  in open symbols; horizontal measurements in (black) circles and vertical measurements in (grey) triangles.

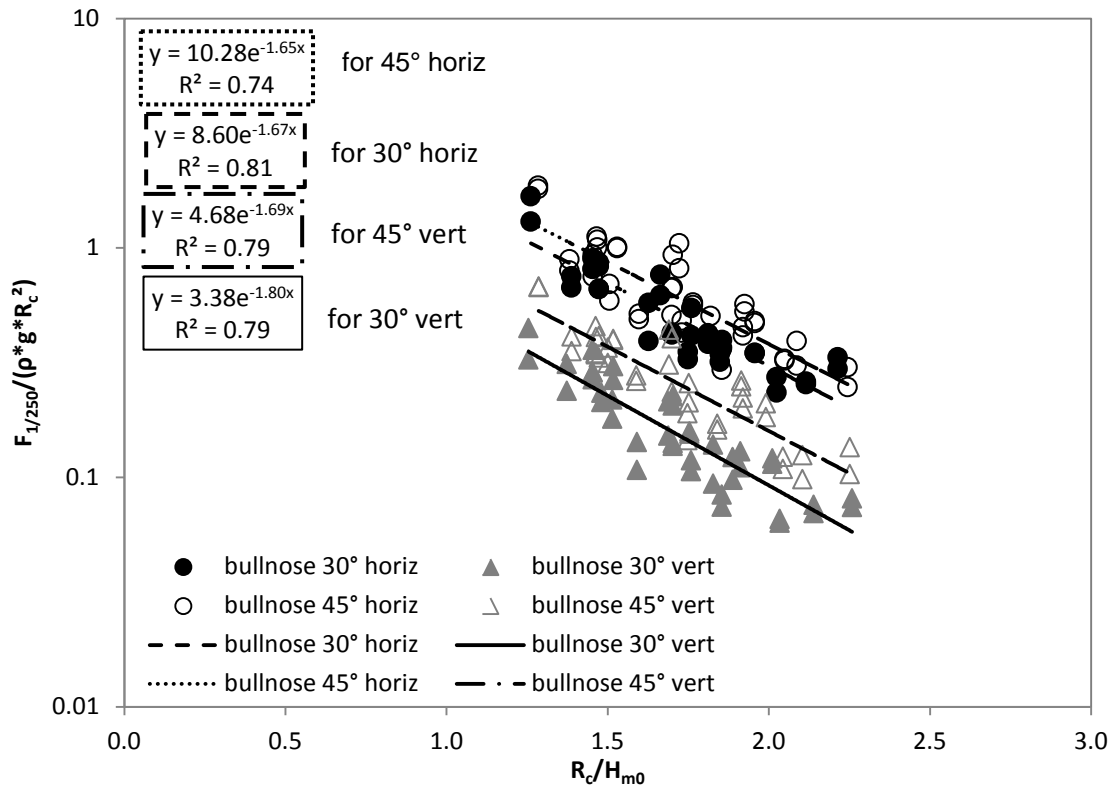


Figure 9: impact forces on a storm wall with bullnose

Consequently, 4 different formulae are given.

$$\frac{F_{1/250}}{\rho \cdot g \cdot R_c^2} = 10.28 \cdot \exp\left(-1.65 \cdot \frac{R_c}{H_{m0}}\right) \quad \text{for } 45^\circ \text{ horizontal} \quad (9)$$

$$\frac{F_{1/250}}{\rho \cdot g \cdot R_c^2} = 8.60 \cdot \exp\left(-1.67 \cdot \frac{R_c}{H_{m0}}\right) \quad \text{for } 30^\circ \text{ horizontal} \quad (10)$$

$$\frac{F_{1/250}}{\rho \cdot g \cdot R_c^2} = 4.68 \cdot \exp\left(-1.69 \cdot \frac{R_c}{H_{m0}}\right) \quad \text{for } 45^\circ \text{ vertical} \quad (11)$$

$$\frac{F_{1/250}}{\rho \cdot g \cdot R_c^2} = 3.38 \cdot \exp\left(-1.80 \cdot \frac{R_c}{H_{m0}}\right) \quad \text{for } 30^\circ \text{ vertical} \quad (12)$$

Figure 9 and formulae (9) to (12) show that the 4 trendlines are quasi parallel. The coefficients in the exponential part of the formulae are thus all nearly equal. The difference in forces only shows in a different coefficient outside the formulae, also known as the a-coefficient in (1).



From a comparison of the  $\alpha$ -coefficients, it is concluded that a 45° bullnose has about 20% higher horizontal forces and about 40% higher vertical forces than a 30° bullnose. The horizontal forces of both bullnoses are a little bit more than twice the vertical forces on the same bullnose.

### Smooth dike slope with promenade

Many coastal zones have a (touristic) promenade at crest level of their dikes. Besides knowing the amount of overtopping coming onto the promenade, it can also be of relevance to know the amount of overtopping discharge at the end of the crest width, because this is the overtopping that is flowing towards the hinterland. The width of the promenade has a reducing effect on the overtopping discharge. 62 tests have been carried out with 3 different promenade widths to study its influence.

The promenade has a 1% or 2% slope to stimulate drainage from overtopping or rainfall back towards the sea. The overtopping discharge is measured at the end of the promenade, see Figure 10. The freeboard  $R_c$  is measured at this location, so includes the height differences on the promenade. The parameters as tested for this geometry are given in Table 3.

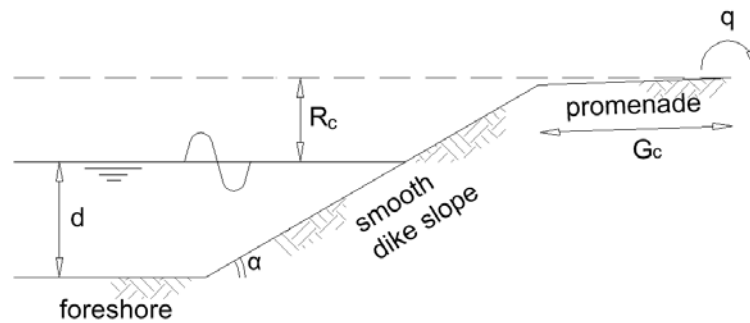


Figure 10: smooth dike slope with promenade

		Tests overtopping
Slope angle of the smooth dike slope	$\cot(\alpha)$	2 and 3
Dimensionless freeboard	$R_c/H_{m0}$	0.85 – 2.70
Dimensionless promenade width	$G_c/L_{m-1,0}$	0.045 – 0.50
Wave steepness	$s_{m-1,0}$	0.009 – 0.020
Wave breaker parameter	$\xi_{m-1,0}$	2.20 – 4.21

Table 3: Summary of the test program on a smooth dike slope with promenade

The influence factor  $\gamma$  to be included in (1) is a function of the dimensionless promenade width  $G_c$  (with  $L_{m-1,0}$  the deep water wave length and  $T_{m-1,0}$  measured at the toe of the structure) and is expressed as follows:

$$\gamma_{prom} = 1 - 0.47 \cdot \frac{G_c}{L_{m-1,0}} \quad (13)$$

In this set-up of course no impacts were measured.

### Smooth dike slope with promenade and storm wall

Overtopping can be further reduced by building a storm wall at the end of a promenade, see Figure 11. 138 tests are carried out with different wall heights and promenade widths to quantify the reduction in wave overtopping. 29 of these tests also contain force measurements on the storm wall. These 29 tests have a fixed promenade width and wall height, which corresponds to a 10m wide promenade and 1.2m high storm wall in prototype, being an optimal solution for the Belgian sea dikes and therefore tested on impacts. The formula for the forces is inherent to the choice of promenade width and wall height. It is advised to only use this formula within the boundaries given in Table 4.

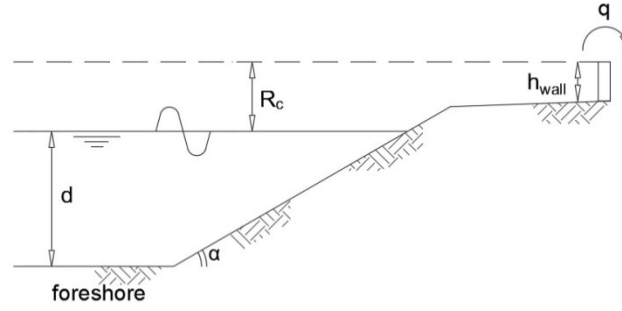


Figure 11: smooth dike slope with promenade and storm wall

		Tests overtopping	Tests impacts
Slope angle of the smooth dike slope	$\cot(\alpha)$	2 and 3	2 and 3
Dimensionless freeboard	$R_c/H_{m0}$	0.85 – 2.56	0.90 – 2.10
Dimensionless wall height	$h_{wall}/R_c$	0.07 – 0.80	0.364 – 0.667
Dimensionless promenade width	$G/L_{m-1,0}$	0.05 – 0.41	0.127 – 0.252
Wave steepness	$s_{m-1,0}$	0.010 – 0.050	0.010 – 0.036
Wave breaker parameter	$\xi_{m-1,0}$	2.26 – 4.79	2.24 – 4.80

Table 4: Summary of the test program on a smooth dike slope with promenade and storm wall

A new influence factor  $\gamma_{prom\_v}$  has to be introduced, as a combination of  $\gamma_{prom}$  (13) and  $\gamma_v$  (3). Van Doorslaer et al. (2015b) shows that simply multiplying both independent influence factors underestimates the reductive effect of a storm wall placed at the end of a promenade. It is a post-overtopping process, where an overtopped bore over the top of the slope once again overtops a (vertical) structure, and due to this changed physical behavior influence factors cannot just be multiplied.

The influence factor becomes

$$\gamma_{prom\_v} = 0.87 \cdot \gamma_{prom} \cdot \gamma_v \quad (14)$$

The 58 impacts (29 tests with 2 parts of the storm wall attached to a force transducer) are given in Figure 12 in a semi logarithmic plot. In agreement with previous geometries, no significant influence of the dike slope angle or wave period is distinguished here. The formula to calculate wave impacts is

$$\frac{F_{1/250}}{\rho \cdot g \cdot R_c^2} = 7.30 \cdot \exp\left(-1.98 \cdot \frac{R_c}{H_{m0}}\right) \quad (15)$$

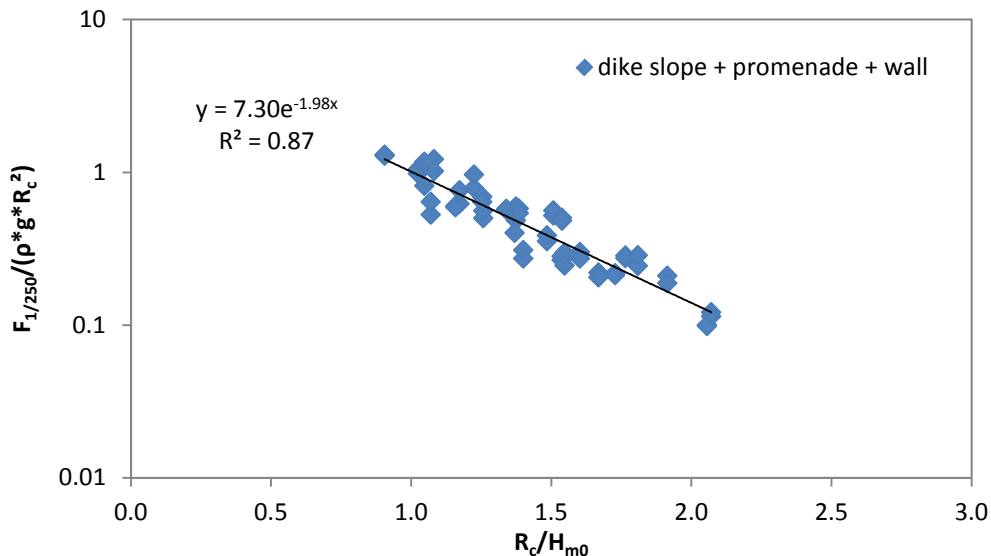


Figure 12: Impact forces on a storm wall at the end of a promenade

### Smooth dike slope with promenade and storm wall with bullnose

The storm wall at the end of the promenade can also have a bullnose to further reduce the overtopping discharge, see Figure 13. 101 tests are carried out to study the extra reducing effect of the bullnose compared to the previous geometry with a storm wall at the end of the promenade. In 64 of these tests, also forces were recorded; horizontal forces in 32 tests and vertical forces in a repetition of these 32 tests. For the force measurements, again no variation in promenade width and wall height are tested. The formulae for impact forces are thereby inherent to these choices of promenade width and wall height, so the formula should only be used within the parameter ranges in Table 5.

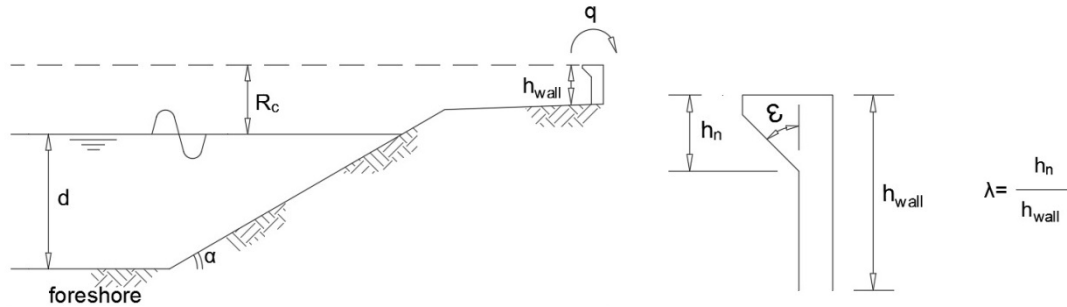


Figure 13: Smooth dike slope with promenade and storm wall with bullnose.

		Tests overtopping	Tests impacts
Slope angle of the smooth dike slope	$\cot(\alpha)$	2 and 3	2 and 3
Dimensionless freeboard	$R_c/H_{m0}$	0.70 – 1.90	0.92 – 1.80
Dimensionless wall height	$h_{wall}/R_c$	0.17 – 0.80	0.36 – 0.67
Dimensionless promenade width	$G_e/L_{m-1,0}$	0.045 – 0.400	0.13 – 0.25
Wave steepness	$s_{m-1,0}$	0.010 – 0.040	0.010 – 0.040
Wave breaker parameter	$\xi_{m-1,0}$	2.15 – 4.80	2.15 – 4.80
Bullnose angle	$\epsilon$	30° and 45°	30° and 45°
Bullnose height ratio	$\lambda$	0.25 – 0.375	0.375

Table 5: Summary of the test program on a smooth dike slope with promenade and storm wall with bullnose

Similar to the previous section, influence factors can not simply be multiplied since physics are different. An overtopped bore on a promenade facing a storm wall with bullnose (like here) is different than when a wave faces a slope with storm wall with bullnose on top (like in Figure 8). This current geometry reduces less than the multiplication of  $\gamma_{bn}$  ((6) or (7)) and  $\gamma_{prom\_v}$  (14). Note that overtopping over this geometry is independent of the wave period (unlike the storm wall with bullnose in front as in Figure 8).

The influence factor becomes

$$\gamma_{prom\_v\_bn} = 1.19 \cdot \gamma_{prom\_v} \cdot \gamma_{bn} \quad (16)$$

The slope angle and wave period have again, just like for all other geometries, no significant influence on the impact forces. The angle of the bullnose ( $\epsilon$ ) and the measurement (horizontal or vertical) do, so the data in Figure 14 are split in four different groups. Separate formulae are given per group.

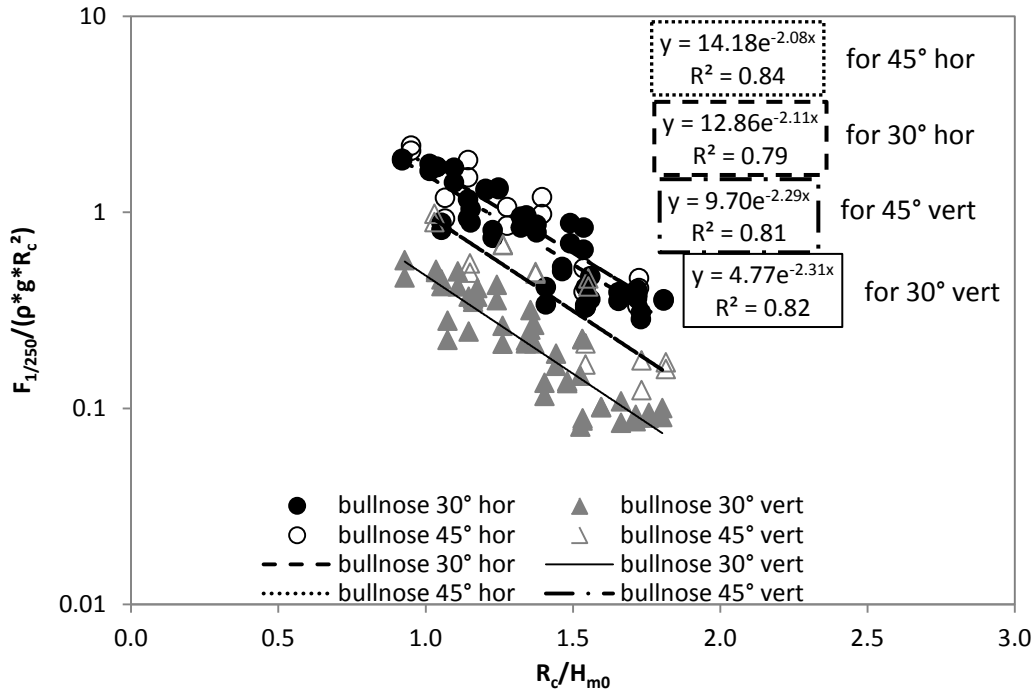


Figure 14: Impact forces on a storm wall with bullnose at the end of a promenade

$$\frac{F_{1/250}}{\rho \cdot g \cdot R_c^2} = 14.18 \cdot \exp\left(-2.08 \cdot \frac{R_c}{H_{m0}}\right) \quad \text{for } 45^\circ \text{ horizontal} \quad (17)$$

$$\frac{F_{1/250}}{\rho \cdot g \cdot R_c^2} = 12.86 \cdot \exp\left(-2.11 \cdot \frac{R_c}{H_{m0}}\right) \quad \text{for } 30^\circ \text{ horizontal} \quad (18)$$

$$\frac{F_{1/250}}{\rho \cdot g \cdot R_c^2} = 9.70 \cdot \exp\left(-2.29 \cdot \frac{R_c}{H_{m0}}\right) \quad \text{for } 45^\circ \text{ vertical} \quad (19)$$

$$\frac{F_{1/250}}{\rho \cdot g \cdot R_c^2} = 4.77 \cdot \exp\left(-2.31 \cdot \frac{R_c}{H_{m0}}\right) \quad \text{for } 30^\circ \text{ vertical} \quad (20)$$

The coefficients in the exponential part of the formula are all close to each other, so the difference in the formulae are mainly in the constant value outside the exponential part (the a-coefficient).

Comparison of these a-coefficients shows that 45° bullnoses have 10% higher horizontal forces, and double the uplift forces. The horizontal forces are 1.5 (for 45° bullnose) to 2.7 (for 30° bullnose) times higher than the vertical forces.

## CONCLUSION

This paper gives 5 different geometries to reduce wave overtopping over a smooth dike slope:

- Smooth dike slope + wall (Figure 6)
- Smooth dike slope + wall + bullnose (Figure 8)
- Smooth dike slope + promenade (Figure 10)
- Smooth dike slope + promenade + wall (Figure 11)
- Smooth dike slope + promenade + wall + bullnose (Figure 13)

651 tests are carried out on dike slopes 1:2 and 1:3 to measure wave overtopping, all with non-breaking waves ( $\xi_{m-1,0} > 2.1$ ). From these 651 tests, 203 include force recordings. For these tests, fixed wall heights and promenade widths are used.

For all different geometries, an influence factor  $\gamma$  is given to be included in (1)

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0.09 \cdot \exp \left[ - \left( 1.5 \cdot \frac{R_c}{H_{m0} \cdot \gamma} \right)^{1.3} \right] \quad (1)$$

For all geometries besides the dike slope with promenade, forces on the storm walls are measured. They are given in the dimensionless formula (2)

$$\frac{F_{1/250}}{\rho \cdot g \cdot R_c^2} = a \cdot \exp \left( -b \cdot \frac{R_c}{H_{m0}} \right) \quad (2)$$

For each different geometry, coefficients a and b are given. For geometries with a bullnose, different coefficients are given for different nose angles 30° and 45°, and for the horizontal forces versus the uplift forces.

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